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# UNITED STATES PATENT APPLICATION

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# A MICROMACHINED RELAY WITH INORGANIC INSULATION

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## PRIORITY INFORMATION

This application claims priority from provisional application Ser. No. 60/421,162 filed October 25, 2002, which is incorporated herein by reference in its entirety.

## FIELD OF THE PRESENT INVENTION

The present invention is directed to a micromechanical relay. More particularly, the present invention is directed to a micromechanical relay with inorganic insulation made utilizing micromachining techniques.

## BACKGROUND OF THE PRESENT INVENTION

Electronic measurement and testing systems use relays to route analog signals. Switching devices used in these systems are required to have a very high off-resistance and a very low on-resistance. MOS analog switches have the disadvantage of non-zero leakage current and high on-resistance.

One example of a prior art microswitch is illustrated in Figure 1. The basic structure is a micromechanical switch that includes a source contact **14**, a drain contact **16**, and a gate contact **12**. A conductive bridge structure **18** is attached to the source contact **14**. The bridge structure **18** overhangs the gate contact **12** and the drain contact **16** and is capable of coming into mechanical and electrical contact with the drain contact **16** when deflected downward. Once in contact with the drain contact **16**, the bridge **18** permits current to flow from the source contact **14** to the drain contact **16** when an electric field is applied between the source and the drain.

Thus, as shown in Figure 2, the voltage between the gate **12** and the source **14** controls the actuation of the device by generating an electric field in the space **20**. With a sufficiently large voltage in the space **20**, the switch closes and completes the circuit between the source and the drain by deflecting the bridge structure **18** downwardly to contact the drain contact **16**.

Switches of this type are disclosed in U.S. Patent No. 4,674,180 to Zavracky <u>et al</u>.; the entire contents of U.S. Patent No. 4,674,180 are hereby

incorporated by reference. In this device, a specific threshold voltage is required to deflect the bridge structure **18** so that it may contact the drain contact **16**. Once the bridge **18** comes into contact with the drain contact **16**, current flow is established between the source and the drain.

To obtain consistent performance the source must always be grounded, or the driving potential between the source and the gate must be floating relative to the source potential. However, this arrangement is not acceptable for many applications.

A preferred arrangement is a device with four external terminals instead of three: a source, a gate, and a pair of drain terminals, disposed such that a driving voltage between the gate and the source actuates the device, and establishes electrical contact between the drain electrodes, but keeps the drain electrodes electrically isolated from the source and gate electrodes. The advantage of this arrangement is that the current being switched does not alter the fields used to actuate the switch. Thus, the isolated contact completes a circuit independently from the circuitry used to actuate the switch. Several electrostatic microrelays of this type have been described in the prior art.

US Patent Number 5,278,368 to Kasano et al. discloses an electrostatic microrelay with a single-crystal silicon cantilever beam suspended above a gate electrode, and a contact bar attached to, but electrically isolated from, the underside of the beam. When the beam is actuated, the contact bar creates an electrical path between a pair of drain electrodes. Additional conductors distributed below and above the beam enable bistable operation. The manufacture of such a device requires the construction and alignment of several layers of conductors and insulators.

Yao and Chang (Transducers '95 Eurosensors IX, Stockholm, Sweden (1995)) have reported a similar device, with the difference that the cantilever beam is made of silicon oxide, and isolates the source from the beam contact without requiring an additional insulating layer.

Gretillat et al. (J. Micromech. Microeng. 5, 156-160 (1995)) have reported a microrelay with a polysilicon/silicon nitride/polysilicon bridge as the mechanical element.

US Patent Number 6,162,657 to Schiele, et al. disclosed a microrelay based on a gold cantilever sandwiched between silicon oxide layers to provide curvature to the beam by residual stress action, and hence improve isolation in the off-state.

A number of electromagnetically actuated microswitches and microrelays have been described in the prior art. The use of electromagnetic actuation limits the extent to which these devices can be miniaturized, and also results in higher power consumption than electrostatic actuation.

Another electrostatic microrelay is disclosed in U.S. Patent No. 5,638,946 to Zavracky. As disclosed by Zavracky and illustrated in Figure 3 of the present application, a micromechanical relay **28** includes a substrate **30** and a series of contacts (**32**, **34**, **36**) mounted on the substrate. The contacts include a source contact **32**, a gate contact **34**, and a drain contact **36**. The drain contact **36** is made up of two separate contacts that are not shown in Figure 3.

A beam **38** is attached at one end **40** to the source contact **32** and permits the beam to hang over the substrate **30**. The entire beam structure **38**, which comprises three separate components (a conductive body component **44** that includes the one end **40** attached to the source contact **32**, an insulative element **42**, and a conductive contact 46), is of sufficient length to overhang both the gate contact **34** and the drain contact **36**.

As noted above, the beam structure **38** includes an insulative element **42** that joins and electrically insulates the conductive beam body **44** from the beam contact **46**. The conductive beam body **44** overhangs only the gate contact **34**. The insulative element **42** is of sufficient length to provide a mechanical bridge or extension between the conductive beam body **44** and the conductive contact **46** such that the conductive contact **46** overhangs the drain contact **36**. In other words, the insulative element **42** provides additional lateral length to the beam structure **38**.

In operation, actuation of the switch permits the beam contact **46** to connect the two separate contacts of the drain contact **36** and allow current to flow from one separate drain contact to the other.

The microrelay described above is based on a metallic cantilever beam. When a voltage is applied between the gate and the source electrodes, the electrostatic force between the beam and the gate electrode pulls the free end of the beam down. The free end or the beam contact is mechanically connected to, but electrically isolated from, the rest of the beam by a piece of insulating material, commonly a polyimide. When the beam is pulled down, a pair of contact bumps on the underside of the beam contact closes the path between a pair of thin film electrodes underneath the contact

The prior art device described above has some advantages relative to the other prior art devices referred previously. The device is fabricated from a single wafer and does not require wafer-bonding steps. It is fabricated using a surface micromachining process, which is generally simpler than a bulk micromachining process. The fabrication process is also a low temperature process relative to Si micromachining processes and traditional semiconductor fabrication processes. These advantages make it possible to build the device cheaply, and also make it feasible to integrate the device with semiconductor integrated circuits, with minimal interference with the semiconductor fabrication process.

However, a disadvantage of the device is that the material of the insulating segment **42** has to meet a number of requirements, some of which may be contradictory. It should electrically isolate the conductive beam contact **46** from the conductive beam body **44**; it should have sufficient mechanical strength and rigidity to prevent excessive bending or breaking of the segment during actuation of the microrelay; it should have good adhesion to the beam body and the beam contact to ensure the mechanical integrity of the device when the microrelay opens and closes repeatedly; it should permit a method of deposition and patterning that is straight-forward and compatible with the rest of the fabrication process; and it should be chemically inert so that the microrelay can operate in a hermetic environment

without being susceptible to contamination of the contacts by out-gassing from the insulating segment.

A practical embodiment of the device with the insulating segment **42** made out of a polyimide has been found to have poor mechanical integrity. More specifically, when the switch opens and closes repeatedly, the polyimide segment **42** loses adhesion with the conductive beam body **44** such that the insulative element **42** along with the conductive beam contact **46** fall off the end of the conductive beam body **44**.

It is also possible that when the relay operates in a hermetic environment, the polyimide material will out-gas, particularly during high temperature cycles, and contaminate the microrelay context.

Therefore, it is desirable to design a microrelay wherein fewer requirements are imposed on the electrically insulating material, so that a microrelay with good electrical performance and mechanical integrity can be realized at low cost.

## SUMMARY OF THE PRESENT INVENTION

One aspect of the present invention is a micromechanical relay. The micromechanical relay includes a substrate; a source contact mounted on the substrate; a gate contact mounted on the substrate; a pair of drain contacts mounted on the substrate; and a deflectable beam. The deflectable beam includes a conductive beam body having a first end and a second end, the first end of the conductive beam body being attached to the source contact. The conductive beam body extends substantially in parallel to the substrate such that the second end of the conductive beam body extends over both the drain contacts. The deflectable beam also includes a beam contact overhanging the drain contacts and an insulator positioned between the second end of the conductive beam body and the beam contact to join the second end of the conductive beam body to the beam contact and to electrically insulate the conductive beam body from the beam contact.

Another aspect of the present invention is a method for making a micromechanical relay. The method forms a source contact, a gate contact, and a pair of drain contacts upon a substrate; forms a sacrificial region over the source contact, gate contact, drain contact, and substrate; forms a conductive beam contact region on the sacrificial region having the drain contacts thereunder; forms an insulative region over the beam contact region; and forms a conductive beam body on the source contact, the conductive beam body being formed further to extend laterally over the sacrificial region and the insulative region, the formed conductive beam body extending laterally substantially over the source contact, gate contact, and drain contact.

## BRIEF DESCRIPTION OF THE DRAWINGS

The present invention may take form in various components and arrangements of components, and in various steps and arrangements of steps. The drawings are only for purposes of illustrating a preferred embodiment and are not to be construed as limiting the present invention, wherein:

Figures 1-3 illustrates prior art micromechanical switches;

Figures 4 and 5 illustrate forming a conductive layer on a substrate and forming contacts therefrom;

Figure 6 illustrates forming a sacrificial region over the contacts and substrate;

Figure 7 illustrates etching a well region in the sacrificial region;

Figure 8 illustrates forming a conductive region to be used in forming the conductive beam contact region;

Figure 9 illustrates forming the conductive beam contact region;

Figure 10 illustrates etching to prepare for forming the conductive beam body and an external connector to the drain contact region;

Figure 11 illustrates forming an insulative region over the conductive beam contact region;

Figure 12 illustrates forming a conductive region to be used in forming the conductive beam body and external connector to the drain contact region;

Figure 13 illustrates etching to electrically isolate the conductive beam body from the external connector to the drain contact region;

Figure 14 illustrates forming further conductive regions to be used in forming the conductive beam body and external connector to the drain contact region;

Figure 15 illustrates one embodiment of an insulated micromechanical switch according to the concepts of the present invention; and

Figure 16 illustrates the section marked as A-A' in Figure 15.

## DETAILED DESCRIPTION OF THE PRESENT INVENTION

As mentioned above, Figures 4 through 15 illustrate a process for constructing an insulated micromechanical switch according to the concepts of the present invention.

More specifically, as illustrated in Figure 4, a substrate is coated, preferably by vapor deposition, with a metallic substance **12**. The metallic substance **12** may be a metal from the group of platinum, palladium, titanium, rhodium, ruthenium, gold, or an alloy containing one of these metals. As illustrated in Figure 5, certain portions of the metal layer **12** are stripped away by standard photolithographic patterning and dry etching techniques, so that electrodes or contacts **121**, **122**, and **123** are formed. Electrode **121** forms a source contact for the switch of the present invention. Moreover, electrode **122** forms a gate contact for the switch of the present invention. As illustrated in Figure 16, the electrode **123** is actually a pair of electrodes 1232 and 1233 such that the switch makes an electrical contact between the electrode pair to complete the electrical circuit.

Upon the formation of the electrodes (contacts) **121**, **122**, and **123**, as illustrated in Figure 6, a metallic layer **14,** which may be titanium or titanium-tungsten, is vapor-deposited upon the substrate **10** and the three electrodes **121**, **122**, and **123**. Upon the metallic layer **14**, a further layer of copper **16** is vapor-deposited. The metallic layer **14** promotes adhesion of the copper layer **16** to the underlying substrate. The combination of the metallic adhesion layer **14** and the copper layer **16** forms a sacrificial layer or sacrificial region that will be removed later on in the process.

Figure 7 illustrates the formation of a well **161** in the copper substrate **16**. This well was formed by covering the copper layer **16** with a photoresist except in the area of the well **161**. In the area of the well **161**, a portion of the copper layer **16** was stripped away to form the well **161**. The well **161** will be used to form a conductive beam contact.

After forming the well **161** of Figure 7, a metallic layer **18,** which may be titanium or titanium-tungsten, is vapor-deposited upon the copper layer **16**, as illustrated in Figure 8. This metallic layer promotes adhesion between the underlying copper layer **16**, and metallic layers to be deposited subsequently. Furthermore, as illustrated in Figure 8, a layer **20**, from the group of platinum, palladium, titanium, rhodium, ruthenium, gold, or an alloy containing one of these metals, is vapor-deposited upon the metallic adhesion layer **18**.

Figure 9 illustrates the formation of a metal contact, from layer **20**, of the switch used to make the electrical connection between the pair of drain electrodes represented by drain electrode **123**. Using standard photolithographic and dry-etching techniques, a portion of the metal layer **20** from Figure 8 is stripped away so as to form a layer **20**, which corresponds solely to the well area **161**.

In Figure 10, the layers **14**, **16**, and **18** have been stripped away using standard photolithographic and dry-etching techniques to form a well **1211** corresponding to the source contact **121**. The well **1211** will be used to contact the conductive beam body to the source contact **121**.

After forming the wells **1211** and **1231** of Figure 10, an insulative layer **21** is deposited. A metallic layer **211**, which may be titanium or titanium-tungsten, is vapor-deposited on top of the insulating layer. The metal layer **211** promotes adhesion between the insulating layer **21**, and the beam layer, which is deposited subsequently. Portions of layers **21** and **211** are removed using standard photolithographic and dry-etching techniques, so that an insulating region is formed over and around the beam contact region or metallic layer **20**. This insulative layer **21**, in the preferred embodiment, is aluminum oxide. However, it is noted that any insulative layer may be suitable, such as silicon oxide or silicon nitride.

The formation of the insulative layer **21** is illustrated in Figure 11. Thereafter, a layer of gold **22** and a metallic layer **24**, which may be titanium or titanium-tungsten, are vapor-deposited over the entire device, as illustrated in Figure 12. The gold layer **22** serves as a seed layer for subsequent formation of the beam by electro-plating. The metallic layer **24** protects the underlying gold layer **22**

during the processing steps immediately following Figure 12, and is removed prior to formation of the beam by electro-plating.

In Figure 13, the gold layer **22** and the titanium layer **24** have been selectively stripped away by standard photolithographic and dry-etching techniques, to form wells **181** and **182**. These wells define the spaces, which will eventually separate the beam from other structures. Figure 14 illustrates the formation of the cantilever beam **28**. This is carried out by first depositing a photoresist layer, and selectively stripping away a portion of it using standard photolithography. The protective layer **24** is then etched away from the section of the device not covered by photoresist. A thick gold layer is then deposited by electro-plating in the section of the device not covered by photoresist, and the photoresist is stripped away.

Figure 15 illustrates the completion of the construction of the insulated micromechanical switch, according to the concepts of the present invention, wherein the sacrificial layers of copper **16** and the adhesion metals **14** and **18** have been stripped away, thereby leaving a free-standing cantilever beam substantially made up of the plated gold layer **28,** and the vapor-deposited gold layer **22**. Moreover, the micromechanical relay includes the insulative layer **21**, preferably aluminum oxide, which is formed between the gold layer **22** and a contact layer **20**.

Figure 16 illustrates the section identified as A-A' in Figure 15. As illustrated in Figure 16, the substrate **10** has formed thereon the drain electrode pair **1232** and **1233**. Above the drain electrode pair **1232** and **1233** is the contact layer **2001**. Between the contact layer **2001** and the conductive beam body **3101** of the micromechanical switch is an insulative layer **2101** and a metallic adhesive layer **3001**.

It is noted that when the microrelay is actuated, the conductive beam body, represented by plated gold **28** and the gold layer **22**, bends downward to bridge the distance between the beam contact **20** and the drain electrodes **123**. During this process, there is little or no bending of the insulating layer **21**. This is because the insulating layer is above, and substantially parallel to, the beam contact **20**.

In contrast, in the prior art of Figure 3, there is substantial bending of the insulating segment **42** during actuation, because the insulating region extends laterally from the beam body **44**, and is substantially co-planar with the beam body **44** and the beam contact **46**. Therefore, in the present invention, the insulating layer is subject to smaller stresses than in the prior art design shown in Figure 3.

Referring to Figure 15, it is noted that the insulating layer 21 in this embodiment of the present invention is substantially enclosed by the beam body **28** and the beam contact **20**. In contrast, in the prior art of Figure 3, only the bottom surface of the insulating layer **42** is attached to the beam body **44** and the beam contact **46**. Therefore, the insulating segment has inherently better adhesion to the beam body and the beam contact in the present invention, than in the prior art of Figure 3.

Due to the smaller stresses and larger attachment area of the insulating layer, the present invention provides improved mechanical integrity such that when the switch opens and closes repeatedly, the insulating layer is less prone to breaking or losing adhesion with the beam. For the same reasons, the requirements imposed on the insulating material, of high mechanical strength and rigidity and good adhesion to the beam material, are less stringent in the present invention than in the prior art design. This makes it possible to consider a wider variety of materials, particularly inorganic materials such as aluminum oxide, for use in the insulating layer. The use of an inorganic material reduces the danger of contaminating the contacts.

As explained above, a contact bar layer or multiple layers is deposited in pattern immediately after the contact tip edge is established. An electrically insulating layer, for example, aluminum oxide, is next deposited, followed by a metallic adhesive layer. The insulator and adhesive layers are then patterned to enclose the contact bar and isolate it from the plated beam. This construction makes it possible to form the insulating region with minimal additions and modifications to the remainder of the microrelay process flow. Moreover, this construction makes it possible to form the insulative region with minimal

modification to the electromechanical properties of the cantilever beam, facilitating easy design of the cantilever beam.

In summary, a micromechanical relay includes a substrate; a source contact mounted on the substrate; a gate contact mounted on the substrate; a pair of drain contacts mounted on the substrate; and a deflectable beam. The deflectable beam includes a conductive beam body having a first end and a second end. The first end of the conductive beam body is attached to the source contact. The conductive beam body extends substantially in parallel to the substrate such that the second end of the conductive beam body extends over both the gate contact and the drain contacts. The deflectable beam further includes a beam contact overhanging the drain contacts and an insulator positioned between the second end of the conductive beam body and the beam contact to join the second end of the conductive beam body to the beam contact and to electrically insulate the conductive beam body from the beam contact.

The beam is deflectable by an electric field established between the gate electrode and the conductive beam body. The beam is deflectable to a first position, the first position being when the beam contact is in electrical communication with the drain contacts in response to an electrical field of a first strength established between the gate electrode and the conductive beam body. In this position, the relay is "on", and electrical current can flow between the pair of drain contacts in response to a voltage applied across the drain contacts. The deflectable beam is deflectable to a second position, the second position being when the beam contact is electrically isolated from the drain contacts in response to an electrical field of a second strength established between the gate electrode and the conductive beam body. In this position, the relay is "off", and no current can flow between the drain contacts.

As noted before the substrate may comprise oxidized silicon or glass; the deflectable beam body may comprise nickel, gold, titanium, chrome, chromium, copper, or iron; the insulator may comprise polyimide, PMMA, silicon nitride,

silicon oxide, or aluminum oxide; and the source electrode (contact), gate electrode (contact), and drain electrode (contact) may comprise platinum, palladium, titanium, tungsten, rhodium, ruthenium, or gold.

While various examples and embodiments of the present invention have been shown and described, it will be appreciated by those skilled in the art that the spirit and scope of the present invention are not limited to the specific description and drawings herein, but extend to various modifications and changes all as set forth in the following claims.